Structure-Foundation Interaction on the Storebælt Link East Bridge

Feld, Tove; Sørensen, Carsten Steen

Publication date:
1996

Document Version
Early version, also known as pre-print

AAU Geotechnical Engineering Papers
ISSN 1398-6465 R 9601

Structure-Foundation Interaction on the Storebælt Link East Bridge

T. Feld, C.S. Sørensen

1996
Foundation Engineering Paper No 3

GEOTECHNICAL ENGINEERING GROUP
AALBORG UNIVERSITY DENMARK

Feld, T., Sørensen, C.S. (1996). Structure-Foundation Interaction on the Storebælt Link East Bridge.

AAU Geotechnical Engineering Papers, ISSN 1398-6465 R9601.

Foundation Engineering Paper No 3

The paper has been published in *Proc. Int. Conf. for Bridge and Struct. Eng. Copenhagen,* pp 809-818.

The **AAU** **G**eotechnical **E**ngineering **P**apers - AGEP - are issued for early dissemination and book keeping of research results from the Geotechnical Engineering Group at Aalborg University (Department of Civil Engineering). Moreover, the papers accommodate proliferation and documentation of field and laboratory test series not directly suited for publication in journals or proceedings.

The papers are numbered ISSN 1398-6465 R<two digit year code><two digit consecutive number>. For internal purposes the papers are, further, submitted with coloured covers in the following series:

Series	Colour
Laboratory testing papers	sand
Field testing papers	grey
Manuals & guides	red
Soil Mechanics papers	blue
Foundation Engineering papers	green
Engineering Geology papers	yellow
Environmental Engineering papers	brown

In general the AGEP papers are submitted to journals, conferences or scientific meetings and hence, whenever possible, reference should be given to the final publication (journal, proceeding etc.) and not to the AGEPpaper.

Presented at Int. Conf. for Bridge and Structure Engineering, Copenhagen, 1996.

[96]

Structure-Foundation Interaction on the Storebælt Link East Bridge

Tove Feld
Civil Engineer
RAMBØLL,
Copenhagen,
Denmark

Carsten S. Sørensen
Civil Engineer
COWI,
Aalborg,
Denmark

Summary

Interaction between structure and foundation in different limit states are described by:

- A verification of an eccentric ship impact - comparing a BEM model including girder, piershaft and soil with a FEM analysis of the pier and the soil beneath it (ALS)
- Three different independent calculation methods to determine the bearing capacity of the anchor blocks (ULS)
- Different methods to predict the directions and size of the settlements (SLS) for both approach piers and anchor blocks are presented.

1. East Bridge Project

In 1986 the Danish government established a political agreement for connecting the island Fyn with the island Sjælland.

The Storebælt Link project entails three major civil engineering contracts (see Figure 1):

- the West Bridge (rail and motorway)
- the bored tunnel (railway), and
- the East Bridge (motorway) being the world's at present longest suspension bridge with a free span of 1624 m.

This paper looks at the interaction between bridgestructure and foundation for the East bridge in the different limit states from a geotechnical point of view.

The East Bridge substructure consist of tree major component (see Figure 2):

- the approach piers
- the pylons, and
- the anchor blocks.

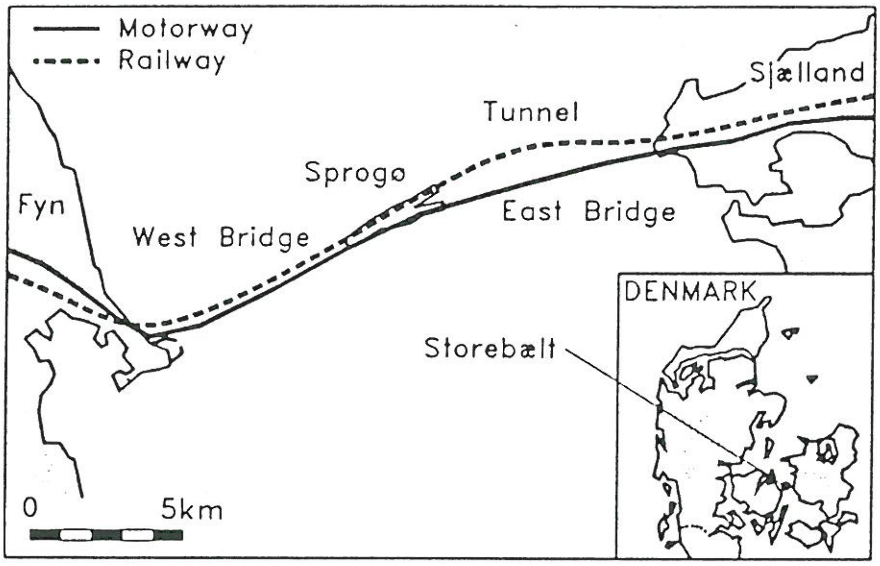


Fig. 1 Location and components of the Storebælt Link

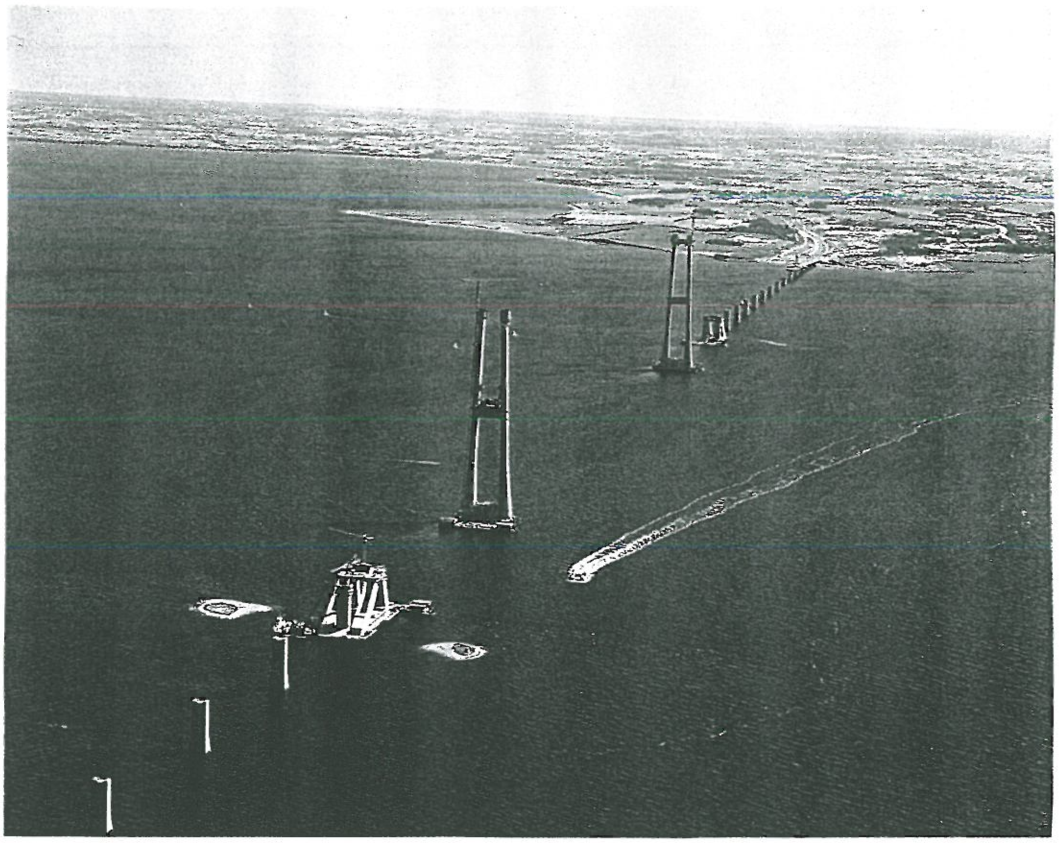


Fig. 2. Birds View of East Bridge, Denmark late 1994.

Generally, the geology consist of two layers of Clay till, with stiffness increasing with depth, underlain by a marl layer and below that, limestone.

Shallow foundation is chosen throughout the project. During the design phase the different limit states lead to a number of challenges in applying advanced analysis method to real life problems

2. Accidental Limit State (ALS)

Based on probabilistic analyses a load scheme for each structure was determined in terms of size and velocity of the colliding ship. The consequences of an impact were determined using a computer program, SIAS62, generating results for inclusion in the overall probabilistic analysis for the entire East Bridge.

2.1 Ship Impact Analysis - Approach Pier

The detailed design of the approach piers included a ship impact analysis, yielding the final dimensions of each pier. In most cases, the critical ship collision with the pier will occur eccentrically, requiring a complete 3D model consisting of sand, relatively hard clay layer, inclined soil interfaces and a local occurrence of soft clay embedded in harder ones under a pier corner.

2.1.1 Boundary Element Model

Generally a simplified, but still advanced computer model, SIAS62, has been used for the analysis of ship impact, ice loading and other accidental loads. The program performs an analysis of the total structure: Pier, bridge girder, neighboring piers and soil, thus including several structural elements in absorbing the impact. In the Boundary Element Model the soil is modelled by simple linear elastic, ideally plastic springs for deflection in three directions and torsion. However these springs reflects only the soil relatively close to the foundation, whereas soil layers more distant are not taken into consideration.

2.1.2 Finite Element Soil Model - Soil Response

To verify the simplified model, independent finite element analyses were carried out. Two independent non-linear finite element programs: ABAQUS and FENRIS were used. Hand calculations were not deemed possible due to the 3D nature of the problem.

2.1.3 Establishment of a Realistic Finite Element Model

Creating a realistic mesh, yet limiting the calculation time was a challenge. The establishment of a suitable 3D mesh to analyze the eccentric ship impact was based on findings from 2D analyses. (simulating a central ship impact.) In the case of a central ship impact , a 2D model is sufficient, thus it is possible to examine the influence of element refinement, special meshing techniques etc.

2.1.4 Comparison between Finite Element Analysis and Boundary Element Model

Figure 3 presents the Load-Displacement curve for both FENRIS and SIAS62. The difference in ultimate bearing capacity is found to be some 10% only.

A comparison of the failure curves of the FEM and BEM analyses, yields that the BEM is more conservative with respect to ultimate bearing capacity - and probably less able to describe the actual behavior of the soil during the serviceability state.

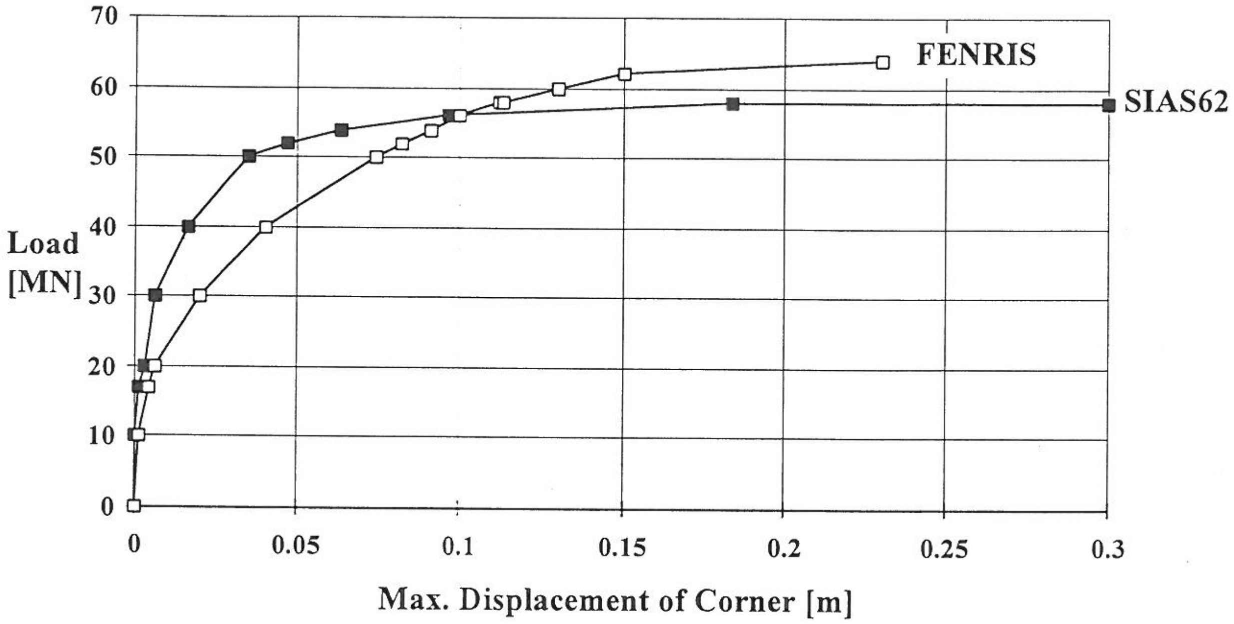


Figure 3 Load-displacement curve for an eccentric ship impact analyzed both in FEM and BEM

The FEM calculation for the eccentric ship impact resulted in larger overturning effects .e.i the pier tilts more and as a result rotates less in the FEM analysis compared to the BEM analysis. This is a natural consequence of the more refined modeling of the soil, including local week areas, lenses etc. in FENRIS. The deformed 3D mesh at failure is depicted in Figure 4

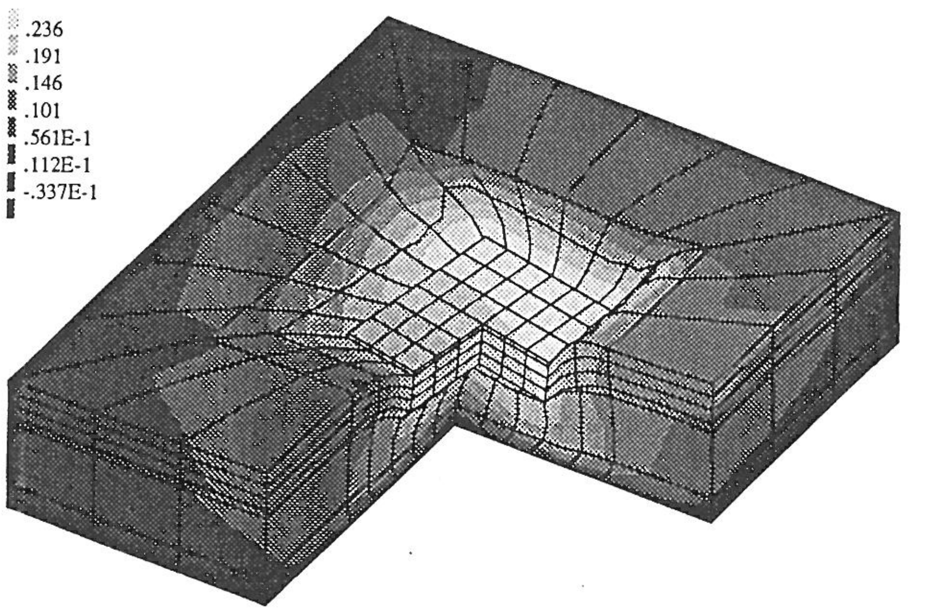


Figure 4 Deformed mesh due to an eccentric ship impact

From the results it was concludes, Feld and Gravgaard (1994), that the soil model in SIAS62 describing the ultimate capacity of a foundation subjected to vertical forces, horizontal forces, overturning moment and twisting moment, results in reasonable capacity prediction in cases where failure is dominated by sliding.

2.2 Pylons

Unlike the approach piers the dimensions of the base (78m by 35m) were primarily dictated by the requirements for structural intregity in the base and lower part of the pylon legs. Requirements to bearings capacity and settlement criteria's were not governing. However FEM analyses were carried out similarly to the approach piers.

2.3 Anchor Blocks

The risk assessment resulted in protective islands in front of each anchor block, diminishing the possibility of a ship collision to negligible ship sizes. Leading the ultimate limit state to impose the dimensions of the foundation of the anchor blocks.

3. Ultimate Limit State (ULS)

The loads from the main cable are carried by two anchor blocks located at 10 m water depth.

3.1 Bearing Capacity - Anchor Blocks

3.1.1 Anchor Blocks

Each anchor block has a rectangular form with the length of 121.5 m and the width of 54.5 m (Figure 5). This base is divided into 3 parts, a front pad of 41.7 m, a middle part of 39.1 m and a rear pad of 40.7 m. Only the front and the rear pads are in contact with the supporting soils.

Both anchor blocks are founded on very stiff to hard preconsolidated clay till. The undrained shear strengths range from 150 - 300 kPa.

As a result of excavation, the top part of the clay till was included in the design with a reduced sliding resistance. This was compensated for by introducing a wedge shaped fill of compacted crushed stone below each of the two pads.

3.1.2 Anchor Block Loads

The loading situation on Figure 5(a) leads to a resulting force shown in Figure 5(b).

Assuming a uniform vertical load distribution for each of the two pads, the two vertical reaction forces are statically determined.

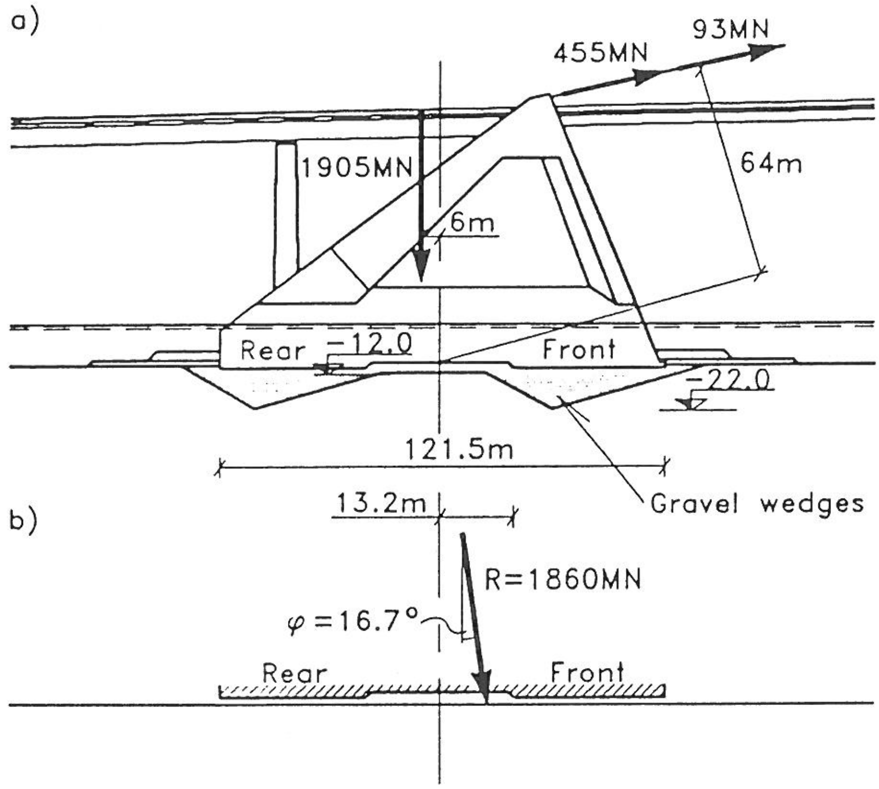


Figure 5 (a) Section of Anchor Block;
(b) Load Resultant acting at Foundation Level

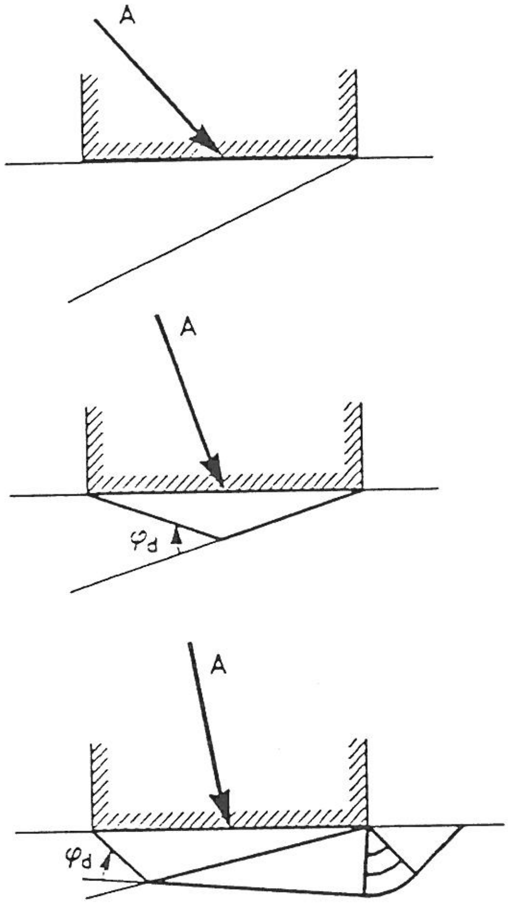
The horizontal shear load can be assumed distributed in such a way that the two foundation pads have the same safety against bearing capacity failure. This assumption is not necessary with a Finite Element Analysis where the total structure is analyzed and where the horizontal shear load is distributed automatically. This, of course, implies that the concrete superstructure has the rigidity and the shear strength needed to distribute the shear loading.

3.1.3 Bearing Capacity Analysis

The bearing capacity analysis was performed both as a traditional deterministic and as an advanced probabilistic ultimate limit state analysis.

Three principally different types of failure modes are possible for each foundation pad depending on load inclination, see Figure 6.

The critical mode for a given case will depend upon geometry, soil strength, and the inclination of the resultant force. The failure mode that involves sliding along the disturbed clay till surface has been discussed earlier in some detail by Mortensen (1983).
A correct solution for the bearing capacity has to be both statically and kinematically admissible.



Failure mode 1:
Sliding in footing/
gravel interface

Failure mode 2:
Sliding in gravel/
till interface

Failure mode 3:
Failure in till

Figure 6 Foundation Pad Failure Modes

It is difficult to find solutions which fulfill both conditions. Therefore, it was decided to use three different and independent calculation methods to determine the bearing capacity of the anchor blocks. The selected methods, all in 2D, included:

- Upper Bound Theory (deterministic and probabilistic)
- Limit Equilibrium Analysis (BEAST)
- Finite Element Analysis (ABAQUS)

Prior to calculation of the bearing capacity of the anchor blocks, the three calculation methods were tested through five bench mark cases. From the results it was concluded, Sørensen et al (1993), that all three methods could be considered as relevant and usable tools for the design procedure. The method which resulted in the lowest value of safety should be the decisive one.

One of the tests was called *The Anchor Block Case* with a geometry and a soil strength nearly identical to those of the real anchor block. The calculation resulting bearing capacities were found to range from 32.3 MN/m to 33.8 MN/m (corresponding to the 2D simplification of strip footings). The rupture figures for the upper bound and ABAQUS analyses are shown in Figure 7 and 8.

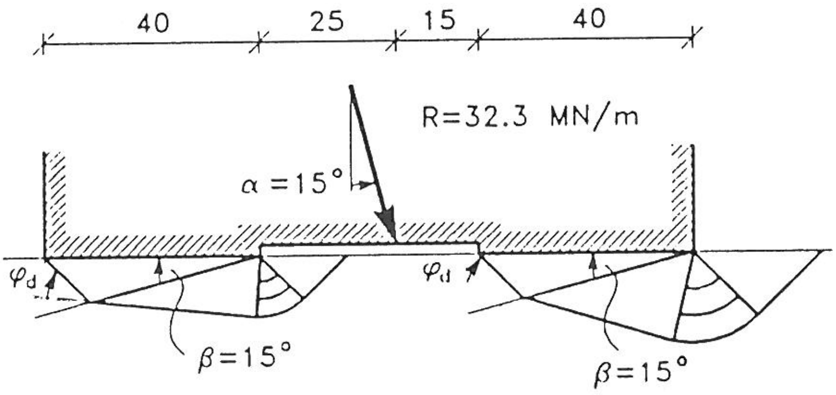


Figure 7 Rupture Figure, Upper Bound Analysis

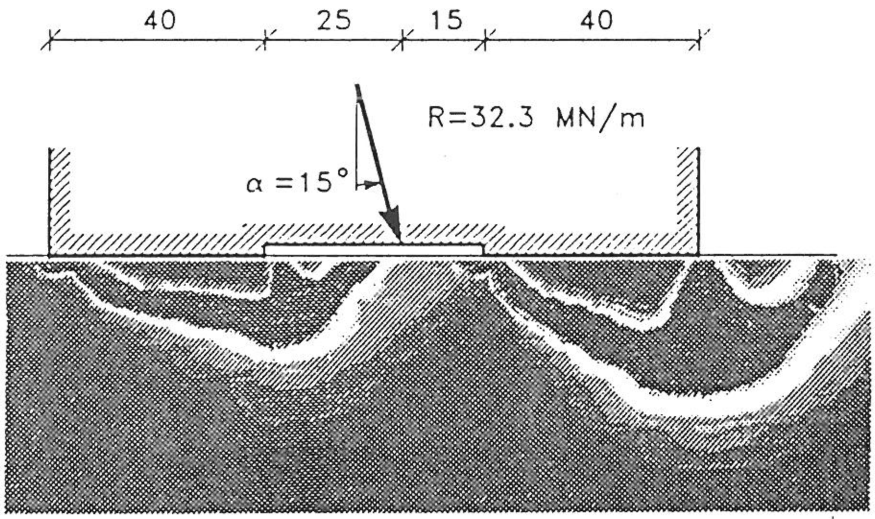


Figure 8 Rupture Figure, ABAQUS Analysis

In addition to these 2D analyses, supplementary 3D analyses were performed for verification of the adequacy of the 2D analyses.

The probabilistic analysis indicated a coefficient of reliability of β = 4.9. This corresponds to high safety class according to the Danish codes.

4. Serviceability Limit State (SLS)

4.1 Anchor Blocks

The size and complexity of the anchor block foundation called for the use of advanced calculation methods. A hand calculation was considered impossible, thus the finite element program ABAQUS was utilized. The following effects were included in the determination of the settlements :

- the complex geometry of the anchor blocks
- the geometry of the gravel wedges
- the variability of the soil conditions, and
- the detailed loading sequence of the anchor block.

The deformation parameters for the soil were determined by advanced laboratory tests, and the stress-strain behavior was well documented.

4.2 Approach Piers

The difficulty in the SLS analysis was applying an analysis true to the nature of the clay. A method based on SHANSEP strength and stress model combined with Bjerrum´s theory of primary and secondary consolidation was established. Sørensen et al (1995) describe this method in more detail.

This model applied the different loading and unloading schemes during the different construction stages while it at all times kept track of consolidation stress, preconsolidation stress and displacements. The model can be updated and changes made, when comparing to the real project allowing for delays etc.

5. Monitoring

5.1 Anchor Blocks

Porepressure gauges and inclinometers have been installed in the gravel wedges and in the underlaying clay till. On-line monitoring of the porepressure and inclination has not begun at this stage. However, when registration starts, the readings will continuously be compared with the design assumptions.

5.2 Settlements

5.2.1 Approach Ramp

An unique possibility to follow in full scale the settlement and creep model established for the clay till occurred during construction of the embankment at Sprogø. The settlement model is based on laboratory tests from the East Bridge project.

Settlement gauges have been installed in the base of the embankment at Sprogø, in the underlaying clay till and finally below the clay till in the marl. Monitoring of these gauges are still on-going (sixth year).

5.2.2 Substructures

From the time of installation of the caissons, settlements observations started and have been recorded ongoing using a DGPS satellite system. The system has been used on the approach piers, the pylons as well as on the anchor blocks. Upon placement of the girders, relative reading have been compiled using traditionally land base survey (trigonometric readings) This monitoring is still on-going (third year).

6. Acknowledgement

The authors are grateful to the Client, A/S Storebæltsforbindelsen, for permission to publish this paper. The design of the East Bridge was performed by CBR, a joint venture between COWI and RAMBØLL and we wish to thank our colleagues in both companies and the Danish Geotechnial Institute, DGI.

7. References

Feld, T. and Gravgaard, J.H. (1994). *Analysis of an eccentric Ship Impact. Proc. of the XIII int. Conf. Soil. Mech. Fndn. Enf., New Delhi, Vol 4, pp. 1687-1690*

Mortensen, K. (1983). *Is Limit State Design a Judgment Killer? The Sixth Laurits Bjerrum Memorial Lecture. Norwegian Geotechnical Institute. Publication No. 148, Oslo 1983.*

Sørensen, C.S., Clausen, C.J.F., Andersen, H. (1993). *Bearing Capacity Analyses for the Great Belt East bridge Anchor Blocks. Limit state design in geotechnical engineering, ISLDS 93, Copenhagen, Danish Geotechnical Society, Bulletin 10, Vol 1, pp 305-312*

Sørensen, C.S, Steenfelt, J. S., Mortensen, J.Kammer (1995). *Foundation of the East Bridge for the Storebælt Link. Proc. of the XI EUR. Conf. Soil Mech. Fndn. Eng, Copenhagen, Vol 5, pp 31-42.*

AGEP: Foundation Engineering papers

1 Sørensen, C.S., Steenfelt, J.S., Mortensen, J.K. (1995). Foundation for the East Bridge for the Storebælt Link. *Proc. 11th Eur. Conf. Soil Mech. & Fndn. Engng. Copenhagen*. Danish Geotechnical Society, Bulletin 11, Vol 5, pp 5.31-5.42. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9506.

2 Steenfelt, J.S., Hansen, H.K. (1995). Key Note Address: The Storebælt Link - a geotechnical view. *Proc. 11th Eur. Conf. Soil Mech. & Fndn. Engng. Copenhagen*. Danish Geotechnical Society, Bulletin 11, Vol 10, pp 10.11-10.40. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9509.

3 Feld, T., Sørensen, C.S. (1996). Structure-Foundation Interaction on the Storebælt Link East Bridge. *Proc. Int. Conf. for Bridge and Struct. Eng., Copenhagen,* pp 809-818. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9601.

4 Sørensen, C.S., Jensen B.S. (1996). Fod-pælens bæreevnetilvækst. *Proc. Nordic Geotechnical Meeting, NGM-96, Reykjavik*, Vol 1, pp 253-258. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9606.

5 Sørensen, C.S., Faber, M.H., Stenstrup, B. (1997). Reliability Based Reassessment of an Existing Pile Foundation. *Proc. XIV Int. Conf. on Soil Mechanics and Foundation Eng., Hamburg*, Sept. 6-12 - 1997, pp 1197-1200. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9709.

6 Steenfelt, J.S. (1997). Type A prediction of settlements for railway box culvert in road embankment on clay till. *Proc. XIVth International Conference on Soil Mechanics and Foundation Engineering, Hamburg,* Vol 2, pp 1037-1044. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9710.

7 Sørensen, C.S., Steenfelt, J.S., Mortensen, J.K., Hansen, Aa., Gluver, H. (1998). Foundation of the East Bridge. In *"East Bridge"*, published by A/S Storebæltsforbindelsen, pp 97-110, ISBN 87-89366-91-3. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9813.

8 Sørensen, C.S., Hededal, O. (1999). Geotecnical design considerations for Storebælt East Bridge and Øresund Bridge. *Proc. IABSE Colloquium, Foundation for Major Bridges-Design and Construction*, New Delhi, India, pp. 25-30 . *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9817.

9 Hededal, O., Sørensen, C.S. (1999). Elasto-plastic foundation analysis of ship collision to The Øresund High Bridge. *Proc. IABSE Colloquium, Foundation for Major Bridges-Design and Construction*, New Delhi, India, pp. 175-180. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9818.

10 Sørensen, C.S., Bisgaard, A., Hededal, O. (1999). Foundation of the Øresund Bridge. *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 1, pp. 609-616. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9819.

11 Steenfelt, J.S., Jørgensen, M.B., Jørgensen, P.O. (1999). Preloaded motorway embankments - an environmentally sound solution for soft soil areas. *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng. ,* 7- 10 June 1999, Vol. 3, pp. 1583-1592. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9820.

12 Feld, T., Petersen, S.J. (1999). Establishment of Foundation Design Parameters for Limestone. *Proc. IABSE Colloquium, Foundation for Major Bridges - Design and Construction,* New Delhi, India, 24-26 Feb. 99, pp. 51-56. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9901.

13 Feld, T. (1999). Development of the load-deformation curve for bridge piers subjected to ship impact. Published in *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 1, pp. 737-742. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9902.

14 Rasmussen, J.L., Feld, T. (1999). Pile Driving Fatigue Damage. A Case Story. Published in *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 2, pp. 577-582. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9903.

15 Feld, T., Rasmussen, J.L., Sørensen, P.H. (1999). Structural and Economic Optimization of Offshore Wind Turbine Support Structure and Foundation. Published in *Proc. OMAE-99, 18th Int. Conf. on Offshore Mechanics and Arctic Engineering,* St.Johns Nfld. Canada July 99. Vol ?, pp. ? *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9904.

16 Sørensen, C.S., Jensen, B.S. (2000). Skråningsstabilitet. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2004.

17 Jensen, B.S., Sørensen, C.S. (2000). Effektivisering af forbelastning ved anvendelse af vertikaldræn. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2005.

18 Feld, T., Leth, C.T., Mikkelsen, H., Steenfelt, J.S. (2000). Nyt laboratorieudstyr til simulering af dynamisk påvirkede sugebøttefundamenter. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2006.